A 2.5-K GM/J-T COOLER FOR MASER LOW-NOISE AMPLIFIERS

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ABSTRACT

A 2.5-K cooler intended for microwave Maser low-noise amplifier cooling applications is described. Maser amplifiers are used as low-noise amplifiers in the National Aeronautics and Space Administration (NASA) Deep Space Network (DSN) ground communication systems. The performance of Maser amplifiers improves dramatically by reducing the operating temperature from the current 4.5-K operating temperature to 2.5 K. The device combines a 4-K Gifford-McMahon (GM) refrigerator with a J-T circuit to provide 180 milliwatts of cooling at 2.5 K. The device is compact and can operate in any physical orientation. A commercial two-stage GM cooler pre-cools the helium J-T circuit flow. The J-T circuit can be simplified compared to existing systems. The 4-K GM stage allows the J-T circuit helium to be cooled below saturation temperature before the J-T expansion. Only two counterflow heat exchangers are necessary. The lower GM operating temperature also allows the use of a single stage compressor for the J-T. The J-T operates with a supply pressure of only 110 Kpa. A commercial scroll vacuum pump is used a compressor. The simplified system can be fabricated for less than half the cost of current 4.5-K Maser coolers.

INTRODUCTION

The NASA Deep Space Network is comprised of 34-m and 70-m-diameter microwave tracking antennas that are used to communicate with spacecraft used for deep space exploration. They are located at three sites: Barstow, California; Madrid, Spain; and Canberra, Australia. These antennas are equipped with cryogenically-cooled low-noise amplifiers, which is a key technology that enables high data-rate communication from space.

The DSN uses a combination of high-electron-mobility (HEMT) amplifers that are cooled with commercial 15 K coolers and traveling wave Masers that are cooled with hybrid Gifford-McMahon (GM)/ Joule-Thomson (J-T) coolers that operate at 4.5 K [1]. Recently an 8.4-GHz Maser cooled with a commercially available 4-K GM cooler was demonstrated [2].

Although HEMT amplifiers are attractive because they are fairly insensitive to physical temperature and can be cooled with off-the-shelf GM coolers, Masers continue to provide the best noise performance of any known amplifier. They are quantum mechanical devices that need to operate at 4.5 K or lower physical temperature. Their performance improves exponentially with temperature. A 1-Kelvin decrease in operating temperature provides a tenfold increase in the amplifier gain.

A new multiple cavity-type Maser for operation at 32 GHz has been designed and is currently being tested at JPL [3]. An 8.4-GHz cavity Maser is also planned. These Masers need to operate at or below 2.5 K for optimum performance

The existing traveling wave Masers would also benefit from a 2.5-K operating temperature, but they require substantially more cooling capacity than the cavity Masers and make operation below 4.5 K unpractical [4].

The cooler described in this paper combines a commercially-available GM cooler operating at or below 4 K to pre-cool a separate J-T circuit. The system uses a single J-T compression stage provided by a commercial scroll vacuum pump that uses no lubricating oil. The system provides 180 mW of cooling at 2.5 K. It is simpler in design and can be fabricated at lower cost than existing DSN 4.5-K GM/J-T systems.

SYSTEM DESCRIPTION

A flow diagram for the cooler is shown in FIGURE 1. The GM cooler pre-cools the J-T circuit flow that provides the final stage of cooling. The GM cooler provides cooling in two stages. The first provides 50 W at 50 K. The second stage provides 1.5 W at 4.2 K.

The J-T ambient supply gas is supplied at 110 Kpa. The J-T gas passes though the first stage counterflow heat exchanger and is cooled by the return gas. It is cooled by the GM first stage to approximately 30 K. The helium is passed through a similar second-stage heat exchanger and is cooled by the GM second stage to approximately 4 K. The flow is then throttled with an externally-adjustable expansion valve to the third-stage operating temperature and pressure. The temperature at the final stage is the saturation temperature of helium at the pressure in the stage. The helium returns through the heat exchangers and is compressed back to the supply pressure and is recycled.

The 4-K GM second-stage operating temperature allows the helium to be cooled below the liquid point before the J-T expansion. This allows the cooler to operate without the third-stage heat exchanger normally used in J-T coolers. Removing the third-stage heat exchanger reduces the cool-down time and system complexity.

During cool-down, helium is supplied from an external helium bottle. The supply gas is regulated to maintain the supply to the cooler at 110 Kpa. When the cooler has reached thermal equilibrium, no more gas is supplied from the external bottle. An external buffer tank allows for small changes in the supply pressure due to gas expansion during changes in the cooling load. An external 130-Kpa relief valve limits the maximum supply pressure.

The complete cooler, excluding the GM cooler compressor, and the external helium supply are mounted on a 1-m^2 platform. The cooler is mounted on a gimbal to allow it to be oriented in different angles to simulate operation on a tipping antenna. A photograph of the assembled cooler is shown in FIGURE 2. FIGURE 3 shows a detailed view of the components inside the vacuum housing.

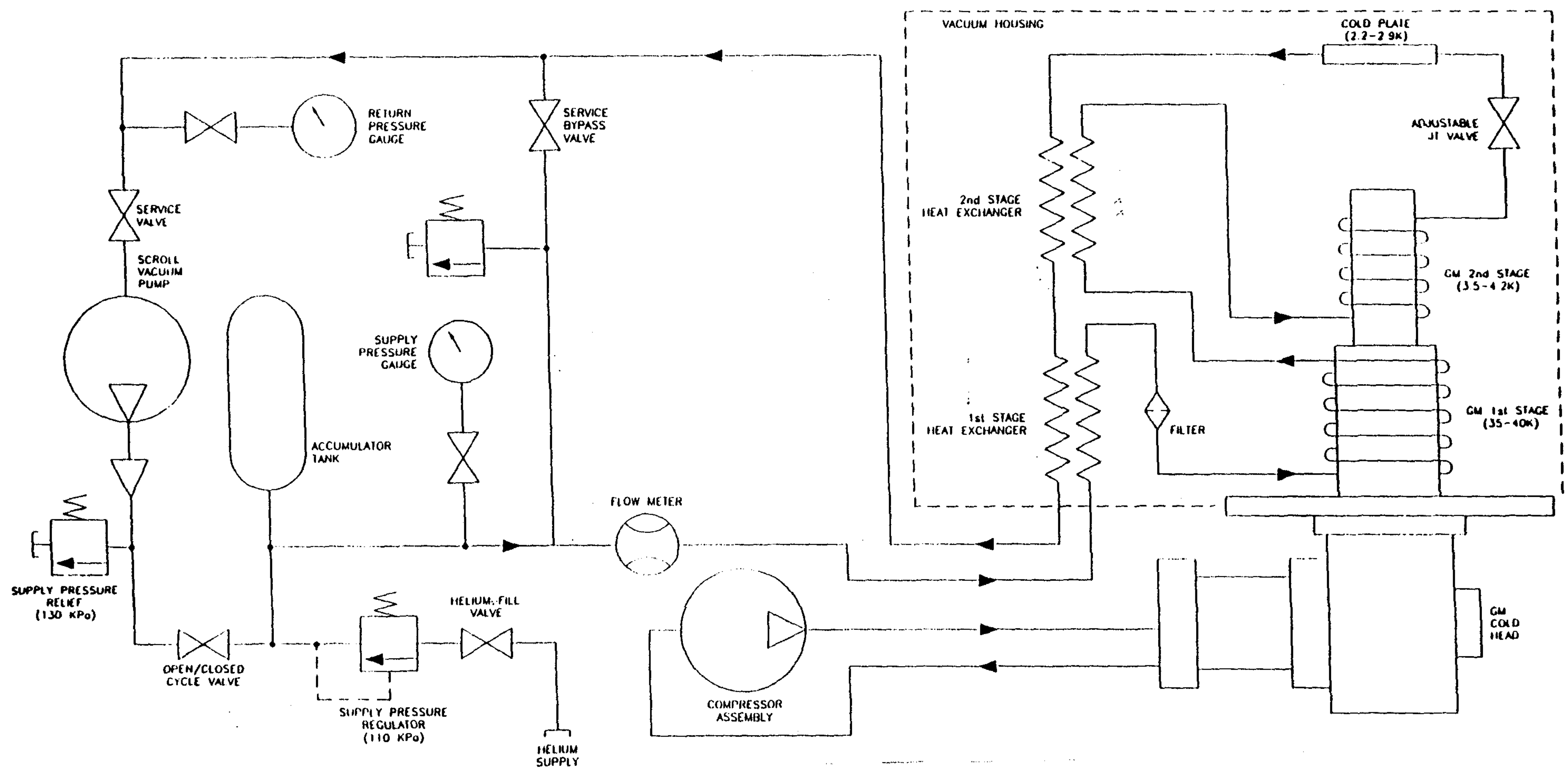

FIGURE 1. Flow Diagram

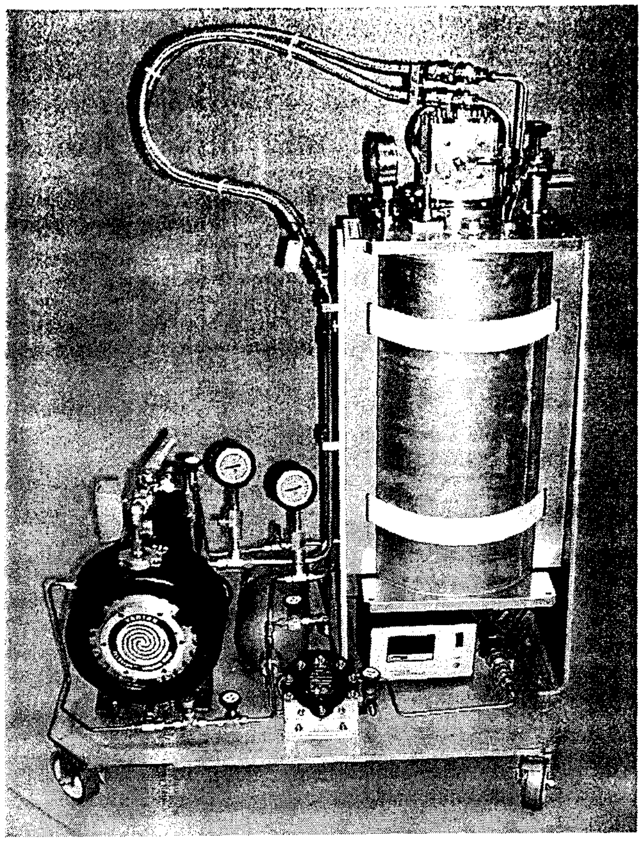

FIGURE 2. View of assembled cooler.

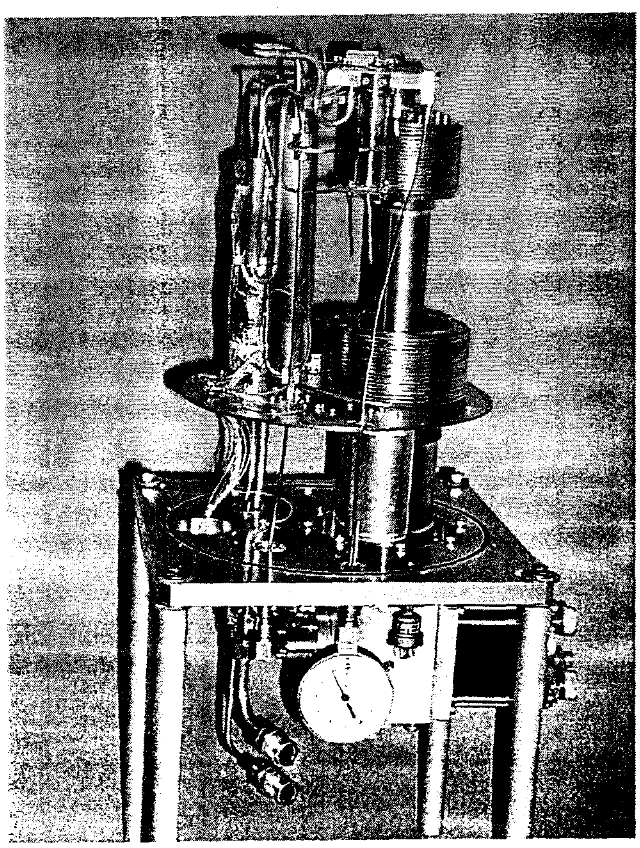

FIGURE 3. Detailed view of components inside vacuum housing.

OPERATING TEMPERATURE AND COOLING CAPACITY

The pressure of the liquid helium controls the ultimate operating temperature of the cooler in the third stage. This is limited by the pumping speed of the scroll pump and the pressure drop in the heat exchangers. For a given pump and heat exchanger, the temperature is simply a function of the J-T flow rate. The flow rate of the system is controlled with an adjustable J-T expansion valve.

Increasing the flow results in a higher pressure drop in the heat exchangers and increases the pressure at the input to the scroll pump. The result is a substantial difference in cooling capacity at different operating temperatures. FIGURE 4 shows the measured cooling capacity as a function of operating temperature. The cooler provides useful refrigeration from 50 mW at 2.2 K to 600 mW at 2.9 K.

COOLING CAPACITY REQUIREMENT

The cooling capacity required for Maser operation is the sum of the passive heat load from mechanical supports, signal inputs, wiring and thermal radiation, and the active load of the microwave "pump" power required for Maser operation. The 32-GHz cavity Maser requires much less pump power than previous designs. A conservative estimate for the 32-GHz cavity Maser pump power is 20 mW.

Another advantage of this system is that the GM cooler provides cooling at 4 K. Careful attention to intercepting the passive load by heat-sinking components to the GM stage will limit the additional passive load to 50 mW or less.

The total cooling capacity required is therefore 70 mW. This leaves an adequate reserve capacity of 110 mW. If the cooling capacity required could be reduced, a slightly lower operating temperature would be achieved.

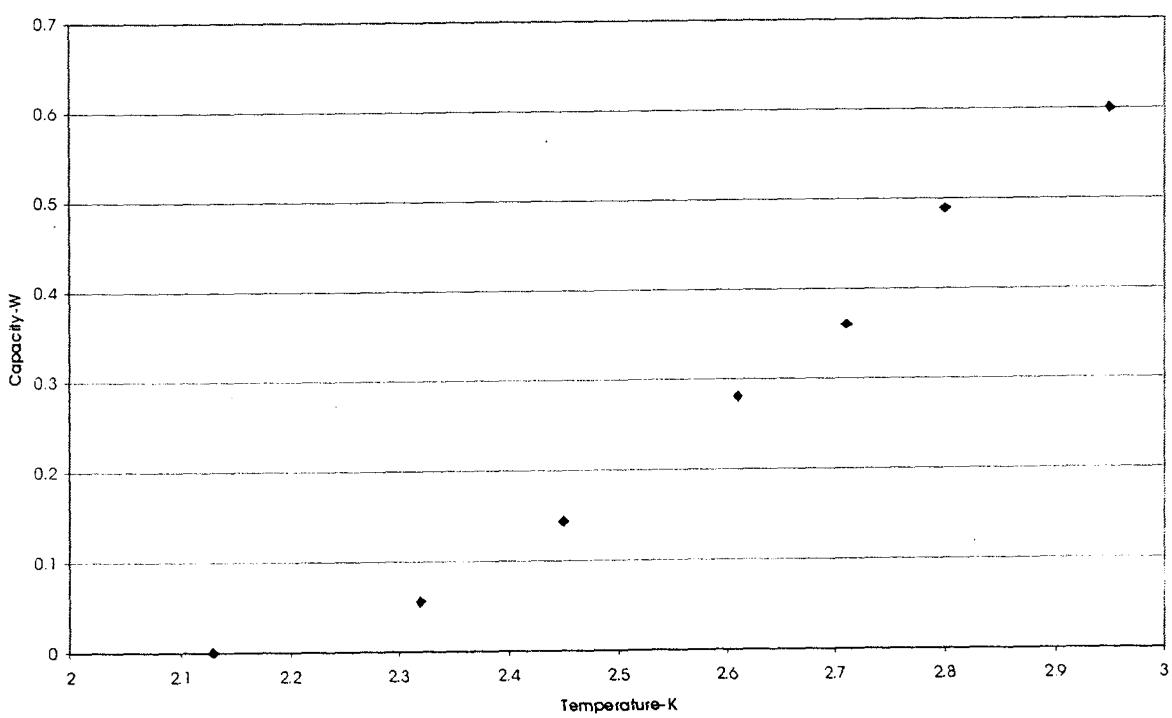

FIGURE 4. Cooling capacity as a function of operating temperature

TEMPERATURE REGULATION

The gain of Maser amplifiers is extremely sensitive to temperature. The requirement for temperature stability over 10 seconds is +/- 3mK. A commercial temperature controller that uses a silicon diode sensor was used in the system. The unit uses a proportional-integral-differential controller to regulate a small current on a resistor on the third stage. The unit also serves as the temperature readout.

The temperature controller also allows accurate and simple measurements of the capacity of the cooler. The controller is simply set to the desired temperature and the device displays the heat applied to achieve the set point temperature. FIGURE 5 is a plot of the temperature stability over 5 minutes. The measurements were made with a calibrated carbon-glass resistor and a computerized data acquisition system. The system measures 14 readings per second. The average temperature was 2.400 K with a standard deviation of 1.53 mK.

OPERATION IN DIFFERENT PHYSICAL ORIENTATIONS

DSN Cassegrain antennas require the Maser to be mounted in the feed cone. The cooler tips in elevation with the antenna. It was thought that the liquid helium in the heat exchangers might be affected by the orientation of the cooler and change the operation of the cooler. To test this, the cooler was mounted on a simple gimbal that allowed the unit to be tilted.

The capacity of the cooler was measured with the GM unit upright, at 45 degrees, 90 degrees (horizontal), 135 degrees, and upside down. No significant change in the capacity was observed at any angle. Thus, the cooler may be mounted at any angle to ease implementation of the system.

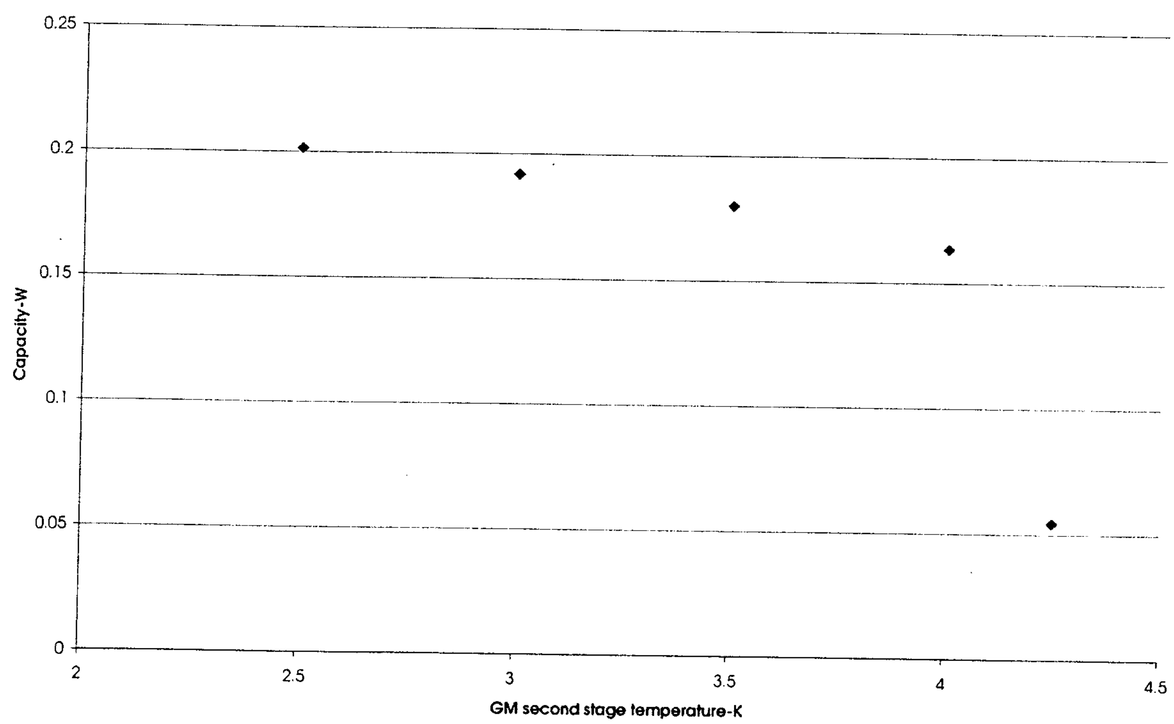

FIGURE 5. Temperature stability over 5 minutes.

SENSITIVITY TO GM COOLER PERFORMANCE

The system is sensitive to the operating temperature of the second stage of the GM cooler. The helium enters the expansion valve to be cooled by the GM cooler to 4 K or lower to provide useful cooling capacity. Typical second-stage operating temperatures are 3.6 to 3.8 K. The data shows only a 10 percent loss in 2.5 K cooling for GM operating temperatures up to 4 K, with a dramatic reduction in cooling above 4.1 K.

At 4.0 K, 1.25 W of cooling are available. The load on the second stage of the GM from the J-T stage is less than 0.3 W. This leaves a reserve of 0.95 W that should be adequate for most uses. Adding a third-stage J-T heat exchanger can reduce the sensitivity of the final-stage capacity to GM temperature. This may be required if the Maser is used in a system with a high passive-thermal load.

RELIABILITY AND OPERATIONAL CONCERNS

The reliability and maintainability of DSN cryogenics systems is a major concern. This design is a substantial change from current DSN closed-cycle coolers. The system has the advantage of not having lubricating oil migration or breakdown in the J-T circuit. The J-T low-pressure circuit operating at less than one atmosphere is a disadvantage. Any substantial leak will allow air in the system. This, however, is unavoidable with any J-T system operating below 4 K and using helium as a working fluid.

The reliability of the scroll pump is also unknown. The manufacturer recommends service at 7000 hours. It is not expected that scheduling pump replacement at 7000 hours should be a problem. The scroll-pump was not tipped with the cooler during the tip tests. More testing will be required if the system is used on a Cassegrain antenna.

The system did operate in the lab continuously for 1200 hours with no failures or measurable degradation in performance. More experience with this system is required before a decision can be made on its long-term reliability. The system hardware was designed for a laboratory demonstration. Work will be required to repackage the system for use in operations.

CONCLUSION

A cryogenic cooler for cooling a cavity Maser was designed fabricated and tested in laboratory conditions. The system produces refrigeration between 2.2 and 2.9 K. It provides 180 mW of cooling at 2.5 K, which is more than adequate for the application. A single stage, oil-less scroll vacuum pump was used for the J-T stage compressor. The operating temperature, cooling capacity, temperature stability and cool-down time are sufficient to meet the requirements for use with the Maser. The system operated continuously for 1200 hours with no problems. It is simple, easy to fabricate and low-cost. It is substantially different than existing DSN systems and will need to be studied further to evaluate its long-term reliability.

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Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacture, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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